Hermetic Packaging of the LAPPDs and Fast Timing Implications for Neutrino-less Double-Beta Decay Searches

Andrey Elagin
University of Chicago
What is $0\nu\beta\beta$?

Compare to normal beta decay: $Z \rightarrow (Z+1), e^-, \bar{\nu}_e$
Why is it interesting?

If observed, neutrino is a Majorana particle, i.e. own antiparticle.

Signature: two electrons with well defined total kinetic energy (2-4 MeV)
What are the challenges?

Rare process (e.g. $T_{1/2}[^{136}\text{Xe}] > 10^{25}$ years): need to get bigger

$$\Gamma = G |M|^2 |m_{\beta\beta}|^2$$

EXO $\sim 32$ kg yr

1 ton $\rightarrow$ 100 kg yr

10 ton $\rightarrow$ 1000 kg yr
What are the challenges?

Tough backgrounds: need to get smarter

2νββ

0νββ

taken from NIMA 650, 1, 73-78

EXO collaboration
PRL 109 (2012) 032505

SS
Idea for $0\nu\beta\beta$ experiments

- Total energy in signal events is well defined.
- Use scintillation light for energy measurements
- Use event topology to suppress backgrounds
  - Signal is two, mostly, “back-to-back” electrons
- Electrons are ~1MeV → above Cherenkov threshold
- Use Cherenkov light to extract directionality of the two electrons
  - All light can be used to constrain location of the vertex
  - Cherenkov light arrives early because of longer wavelength and delay of the scintillation process
Emission Spectra

Simulation of 5 MeV electrons in KamLAND scintillator

5 MeV is a little higher for $0\nu\beta\beta$ search but much lower than typical energies where cherenkov light is being considered.

Seems to be a reasonable choice to test separation between Cherenkov and scintillation.

All photons below 360nm get absorbed
Cherenkov vs Scintillation

Simulation of 5 MeV electrons in KamLAND scintillator

Use early light to extract directionality

A shift between cherenkov and scintillation spectra is a plus
Reconstruction: vertex

Step 1: find vertex (adapted from water cherenkov)
- Assume all light is emitted from a single point (~3 cm track in a ~6 m detector)
- For light emission from a single point any 4 photons (quadruples) would be sufficient to solve for vertex
- With all „real world“ effects we use 400 randomly chosen quadruples and select the one which fits the best to the full ensemble of all photon hits
- Goodness of the fit is based on the distribution of „point time residuals“ (the difference between actual hit time and predicted time of flight from the vertex)

For $i=1\ldots4$:

$$(x_i - x_0)^2 + (y_i - y_0)^2 + (z_i - z_0)^2 = v(t_i - t_0)^2$$

$v$ is the speed of light in the media

Time residuals $dT = (t_j - t_0)$, where $j=1\ldots N_{all}$

The most narrow $dT$ distribution is the closest to the true vertex
Step 2: find direction

- Cherenkov light is directional
- Timing cut enhances the purity of the Cherenkov light
- The centroid of all vectors pointing from the vertex is a good measure of the direction of the track
Directionality of 5 MeV $e^-$

Measuring Directionality in Double-Beta Decay and Neutrino Interactions with Kiloton-Scale Scintillation Detectors

C. Aberle,¹ A. Elagin,² H. J. Frisch,² M. Wetstein,² and L. Winslow¹

¹University of California Los Angeles, Los Angeles, CA 90095, USA
²University of Chicago, Chicago, IL 60637, USA

(Dated: July 23, 2013)

arxiv:1307.5813

Large liquid-scintillator-based detectors have proven to be exceptionally effective for low energy neutrino measurements due to their good energy resolution and scalability to large volumes. The addition of directional information using Cherenkov light and fast timing would enhance the scientific reach of these detectors, especially for searches for neutrino-less double-beta decay. In this paper, we develop a technique for extracting particle direction using the difference in arrival times for Cherenkov and scintillation light, and evaluate several detector advances in timing, photodetector spectral response, and scintillator emission spectra that could be used to make direction reconstruction a reality in a kiloton-scale detector.

5 MeV electrons are very promising even with a very simple reconstruction
What about Lower Energies?

Light yield: Cherenkov vs scintillation

\[ \frac{1}{2} Q \left( ^{116}\text{Cd} \right) = 1.4 \text{ MeV} \]

\[ \frac{1}{2} Q \left( ^{48}\text{Ca} \right) = 2.1 \text{ MeV} \]
What about Lower Energies?

- With 100ps timing, the vertex is constrained within 4-6 cm and the directional information can be extracted even for ~1MeV electrons.

- The next major step is to compare "back-to-back" 0νββ events with 2νββ background.
Candidate Isotopes for $0\nu\beta\beta$

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Endpoint</th>
<th>Abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}\text{Ca}$</td>
<td>4.271 MeV</td>
<td>0.0035%</td>
</tr>
<tr>
<td>$^{150}\text{Nd}$</td>
<td>3.367 MeV</td>
<td>5.6%</td>
</tr>
<tr>
<td>$^{96}\text{Zr}$</td>
<td>3.350 MeV</td>
<td>2.8%</td>
</tr>
<tr>
<td>$^{100}\text{Mo}$</td>
<td>3.034 MeV</td>
<td>9.6%</td>
</tr>
<tr>
<td>$^{82}\text{Se}$</td>
<td>2.995 MeV</td>
<td>9.2%</td>
</tr>
<tr>
<td>$^{116}\text{Cd}$</td>
<td>2.802 MeV</td>
<td>7.5%</td>
</tr>
<tr>
<td>$^{130}\text{Te}$</td>
<td>2.533 MeV</td>
<td>34.5%</td>
</tr>
<tr>
<td>$^{136}\text{Xe}$</td>
<td>2.479 MeV</td>
<td>8.9%</td>
</tr>
<tr>
<td>$^{76}\text{Ge}$</td>
<td>2.039 MeV</td>
<td>7.8%</td>
</tr>
<tr>
<td>$^{128}\text{Te}$</td>
<td>0.868 MeV</td>
<td>31.7%</td>
</tr>
</tbody>
</table>

Advantage of quantum dot doping:
- Narrow the scintillation spectrum
- Shift scintillation spectrum to shorter wavelength
- Dope with metals which can undergo $0\nu\beta\beta$

Quantum dot doped scintillators

Common materials are CdS, CdSe, CdTe

Work by UCLA group
C.Aberle, J.J.Li, S.Weiss, and L.Winslow

This is another lunch topic!
Event Topology

100 „signal-like“ events (5MeV electrons back-to-back)

100 „bkg-like“ events (5MeV electrons at 90 degree)

Cherenkov light only, no time cut, 100% light collection
Spherical Harmonics

Real-value basis:

\[
Y_{\ell m} = \begin{cases} 
\frac{1}{\sqrt{2}} \left( Y_{\ell}^m + (-1)^m Y_{\ell}^{-m} \right) = \sqrt{2} N_{(\ell,m)} P_{\ell}^m(\cos \theta) \cos m\varphi & \text{if } m > 0 \\
Y_{\ell}^0 & \text{if } m = 0 \\
\frac{1}{i\sqrt{2}} \left( Y_{\ell}^{-m} - (-1)^m Y_{\ell}^m \right) = \sqrt{2} N_{(\ell,|m|)} P_{\ell}^{|m|}(\cos \theta) \sin |m|\varphi & \text{if } m < 0.
\end{cases}
\]

\[
f(\theta, \varphi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} f_{\ell m} Y_{\ell m}(\theta, \varphi).
\]

\[
N_{(\ell,m)} \equiv \sqrt{\frac{(2\ell + 1) (\ell - m)!}{4\pi (\ell + m)!}}.
\]

\[
f_{\ell}^m = \int_{\Omega} f(\theta, \varphi) Y_{\ell}^m(\theta, \varphi) \, d\Omega = \int_{0}^{2\pi} d\varphi \int_{0}^{\pi} d\theta \sin \theta f(\theta, \varphi) Y_{\ell}^m(\theta, \varphi).
\]

L2 norm

„Power“ (rotation invariant)

\[
\int_{\Omega} |f(\Omega)|^2 \, d\Omega = \sum_{\ell=0}^{\infty} S_{ff}(\ell)
\]

\[
S_{ff}(\ell) = \sum_{m=-\ell}^{\ell} |f_{\ell m}|^2
\]
Look for the difference between black (back-to-back) and blue (90-degree) lines.

Red line is for comparison with single electron events.

\[ S_{ff}(\ell) = \sum_{m=-\ell}^{\ell} |f_{\ell m}|^2 \]

\( S_1 \) event-by-event fluctuations

These \( S_i \) are calculated for combined hit distribution of 100 events.
$S_1$ as function of time cut

I like this strong dependence on time because with fast photo-detectors we may be able to follow the time evolution of spherical harmonics and use this information in reconstruction.
$S_1$ as function of electron energy

Note Y axis range, the dependence isn't too strong
What's Next?

- Compare simulated 0νββ events with 2νββ
- Consider events off center

Now, I will talk about LAPPD and Hermetic Packaging
Large Area Picosecond Photo Detectors

Transformational Change

- Large area
- Fast timing
- Inexpensive
LAPPD Components

MicroChannel Plates

Hermetic Packaging

Electronics/Integration

Photocathodes
Glass Package (20x20cm²)

- Cheap, widely available float glass
- Anode is made by silk-screening
- Flat panel
- No pins, single HV cable
- Modular design
- High bandwidth 50 Ω object - designed for fast timing

Ceramic body packaging is a parallel (and collaborative) effort at Berkeley SSL
MCP Fundamentals

Conventional Pb-glass MCP
expensive glass processing

Incom glass substrate
cheap glass
Large-Area MCPs

Micro-Capilary Arrays by Incom

- **Material:** borosilicate glass
- **Area:** 20x20cm²
- **Thickness:** 1.2mm
- **Pore size:** 20 µm
- **L/D ratio:** 60:1
- **Open area:** 65-83%
MCP by Atomic Layer Deposition (ALD)

Beneq reactor for ALD
@Argonne National Laboratory

ALD Process for MCP Coating
Developed by
A. Mane, J. Elam

A) Porous glass
Resistive coating ~100nm (ALD)
Emissive coating ~ 20nm (ALD)
Conductive coating (thermal evaporation or sputtering)

33mm plate
8x8" plate
System Integration: "Demountable"

Demountable 1.0
(May 2012)

Demountable 3.0
(Sep-Dec 2012)
Performance

Differential time resolution up to ~ 5ps
Time-of-flight resolution ~ 60ps
Spatial resolution < 1mm

90cm long anode!
RSI Invited Article

Hermetic Packaging
Frit Seal

J. Gregar, M. Minot

1) Attach pump out tube to 8.66x8.66" frame

2) Apply schott #G018-223 K3 frit paste to frame

3) Fire the frit (many trials to optimize parameters)

4) Prepare for anode plate frit sealing

5) Position anode on top of the frame

6) Add weight

- Tile bases are reliably reproducible
- Mechanical and vacuum properties have been tested
Top Seal

How to close frit sealed tile base at the top and stay at moderate temperatures? "Top Seal" problem

Use indium or indium alloys
- soft metal
- low melting point
  (157C for pure In, 72C for InBi)
- essentially zero vapor pressure
- indium-glass seals are successfully used by industry

Parallel efforts: „Hot Seal“ and „Cold Seal“ (or “Compression Seal“)
Hot Seal

Step 1: apply melted indium onto the glass

Step 2: bring parts into contact and press

Step 3: pump from open side and leak check

Prerequisites for leak-tight seal

- Strong Indium-Glass bond
- Strong Indium-Indium bond
Phase I (in air)

- Indium seal fundamentals
  - interface (good adhesion of indium to the glass surface)
  - oxide formation

- Proof of principle using 1x1" test samples
  - little oxidation (assembly is fast)
  - many successful reproducible leak tight samples

- Several (>10) attempts to make 8x8" seal
  - oxide formation becomes limiting factor (slow assembly)
  - best result is a part with $10^{-6}$ cc/s leak at a single pinpoint

...indium oxidizes quickly...
Phase II (in inert atmosphere)

Phase IIa (in inert atmosphere)

Nitrogen filled glove box:
\( \text{O}_2 \) and \( \text{H}_2\text{O} \) concentration ~5ppm

...indium doesn't stick to glass if no \( \text{O}_2 \)...

Phase IIb (add NiCr-Cu layer)

Borrowed from SSL seal
(200nm of NiCr+Cu)

Known facts:

- Indium wets copper surface
  - Alloy is formed at the interface over time
- NiCr interface to glass is essential
  - NiCr is a good match to glass in terms of thermal coefficient
  - Cu would not stick to bare glass but does so on NiCr
Total 8 small size seals made: 5 are leak tight
3 have leaks (oxidation of Cu surface or electroding peeling off the glass)

NiCr-Cu coating of 1” samples done by
D. Walters (ANL)
M. Kupfer (UIC)
J. Williams (ANL-HEP)
C. Liu (ANL-APS)
Q. Guo (UChicago MRSEC)

Shear tests results

Leak tight samples:
- Bare glass #1 190 lbs
- Bare glass #2 278 lbs
- Bare glass with groove 268 lbs
- Cu coated glass #3 390 lbs
- Cu coated glass #4 345 lbs

Samples with a leak:
- Bare glass #4 47 lbs
- Cu coated glass #1 213 lbs
- Cu coated glass #2 221 lbs
Sealing 8x8" parts
Testing NiCr-Cu-In Interface

Coating goes away if re-heated to 180°C
Photos from Metallurgical Microscope (by H.L.Clausing)

Thick side

Thin side

Cu layer dissolves in indium
Switched to InBi alloy (melting point 72°C)
No signs of Cu scavenging by InBi

Why pure In works on 1x1“ samples?
- faster assembly (less time at high temperature)
- less mechanical rubbing
400cm² seal with 2.75 mm window

August, 2013

First leak tight 8x8“ seal using LAPPD glass parts
Leak Test

Many tricks to avoid glass cracking when the pump starts

- Leak checker sensitivity
  $10^{-8}$ cc/s of He
- Leak test lasted for 1 hour
- No leaks found!
Next Steps

- Test reproducibility of the “hot seal” recipe
- Move forward with tile assembly
- Try to make photo-cathode by In-Situ Photo-Cathode Synthesis (possible lunch topic)